UCRL-JC-121153
PREPRINT

TPX Superconducting Cable-in-Conduit 1995 Design and Development Progress

J. P. Zbasnik, N. N. Martovetsky, S. M. Hibbs,
J. H. Schultz, R. D. Pillsbury Jr., J. C. Citrolo

This paper was prepared for submittal to the
Proceedings of the 16th IEEE/NPSS Symposium on Fusion Engineering
Champaign, Illinois
September 30 - October 5, 1995

September 29, 1995

Lawrence Livermore National Laboratory

TPX Superconducting Cable-In-Conduit 1995 Design and Development Progress

J. P. Zbasnik, N. N. Martovetsky, S. M. Hibbs
Lawrence Livermore National Laboratory, Livermore, CA 94550

J. H. Schultz, R. D. Pillsbury, Jr.
Massachusetts Institute of Technology, Plasma Fusion Center, Cambridge, MA 02139

J. C. Citrolo
Princeton Plasma Physics Laboratory, Princeton, NJ 08543

ABSTRACT

A unique feature of the magnet system for the Tokamak Physics Experiment (TPX) is that all the magnets are superconducting. With the exception of the outer poloidal coils, the magnet system uses Nb_3Sn cable-in-conduit conductor; the outer poloidal coils use Nb-Ti cable-in-conduit conductor. We describe the current TPX conductor design and present a progress report on the conductor development. Our strand development contracts have resulted in demonstrating that at least two vendors can produce Nb_3Sn strand which meets the TPX specification. Subcable testing gives confidence that the TPX conductor will satisfy the magnet operational requirements. Fabrication of full-size conductors is underway and tests on these will give verification that the TPX conductor meets the operational requirements. Our industrial cabling and sheathing contract to produce demonstration conductor using copper strands is exploring a production technique that differs from the conventional tube mill approach.

INTRODUCTION

The Tokamak Physics Experiment (TPX), an advanced steady state plasma physics machine to be built at the Princeton Plasma Physics Laboratory, was to be the world's first Tokamak with a complete set of superconducting main coils. An overview of the TPX Magnet System is presented by G. A. Deis, et al. [1] and the Poloidal Field (PF) system is discussed by H. Calvin, et al. [2] elsewhere in this conference. All of the TPX coils will use Cable-in-Conduit-Conductors (CICC) cooled with flowing supercritical helium. The Toroidal Field (TF) coils will require a Nb_3Sn superconductor with a copper to noncopper ratio of 2.5:1, the Central Solenoid (CS) and PF 5 will use a Nb_3Sn superconductor with a copper to noncopper ratio of 3.5:1, and PF 6 and PF 7 will use Nb-Ti superconductor with a copper to superconductor ratio of 2.5:1. The conduit material for the Nb_3Sn conductors will be Incoloy 908, a ferromagnetic material developed especially for this purpose to survive the Nb_3Sn reaction conditions and to match the thermal contraction of the superconducting composite [3]. The Nb-Ti superconductor will be sheathed with 316LN material, an austenitic stainless steel alloy well suited for cryogenic applications [4].

SUPERCONDUCTOR DESIGN CRITERIA

Table 1 below lists the more relevant superconductor design criteria adopted by the TPX project for use in determining design adequacy [5]. In certain cases, the TPX criteria are more aggressive than those adopted by the International Thermonuclear Experimental Reactor (ITER), but we feel our criteria are justified by our experimental results.

Table 1
TPX Conductor Design Criteria

Parameter	Value
Temperature Margin, $T_{cs} - T_{bath}$	> 1 K
Temperature Headroom, $T_{cs} - T_{inlet}$	> 2 K
Energy Margin, $H_{cable(Tcs)} - H_{cable(Tbath)}$	> 300 mJ/cc
Energy Headroom, $H_{cable(Tcs)} - H_{cable(Tinlet)}$	> 600 mJ/cc
Energy Headroom Safety Factor, Energy Deposited / Energy Headroom	> 2
Fraction of Critical Current	< 0.6
Cable Space Helium Fraction	35 % to 45 %
Recovery Power Balance, W/m^2-K $J_{cu}^2 \rho_{cu} A_{cu} / P_w (T_c - T_{bath})$	< 1000 for Nb3Sn, < 600 for Nb-Ti

CONDUCTOR DESIGN

The conductor designs shown in Fig. 1- 3 reflect the design state at the time of the magnet system Preliminary Design Review which was held in September, 1995.

A rather unique feature of the TPX conductors is the incorporation of internal quench detection sensors directly in the cable. Two types of quench detection sensors are under consideration: coaxial wire voltage sensors and fiber optic temperature sensors. Further information on this aspect can be found in several other papers presented at this conference [6-9]. Recent experimental results suggest that the best location for the voltage sensors is in the center of the next-to-last cabling stage.

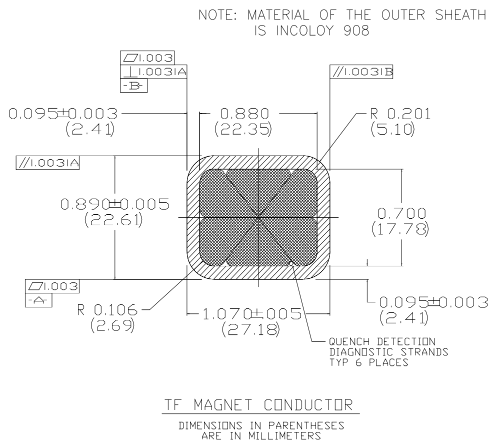

Fig. 1 TPX TF Conductor

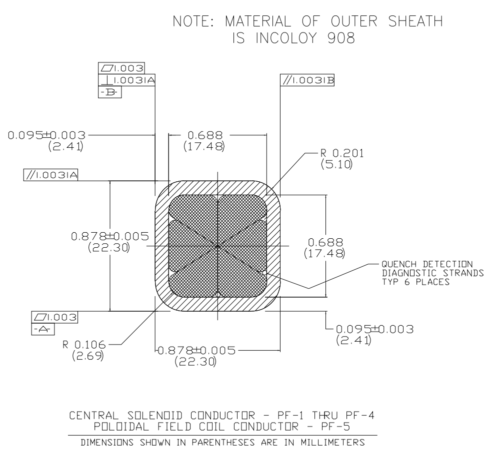

Fig. 2 TPX CS & PF-5 Conductor

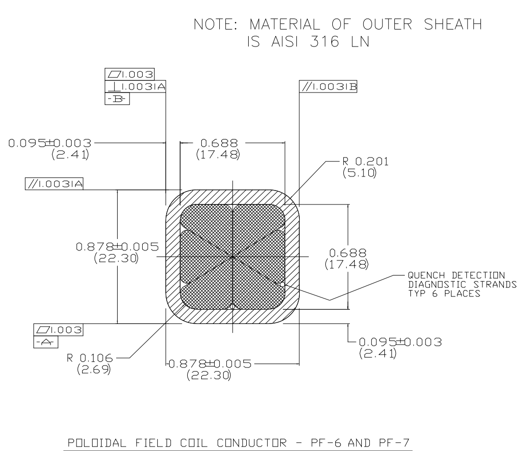

Fig. 3 TPX PF-6 & PF-7 Conductor

CONDUCTOR DEVELOPMENT PLAN

The elements of our overall plan to develop the conductors for TPX is presented below in Fig. 4. The plan is not a stand-alone plan, but is integrated with other Lab effort in quench detection R&D and magnet fabrication R&D which is being done by the magnet subcontractors. The connection to quench detection R&D is obvious since we need to incorporate sensors in the cable space to obtain the needed signal to noise ratio to allow fast enough detection to protect the coils. The magnet fabrication R&D generated requirements on material property consistency to allow precision bending and forming over the entire length of conductor, and the studies carried out on the thermal behavior of cross-sectionally full-size winding pack mockups will need to be reconciled with the Vendor-proposed time-temperature profiles needed to form the Nb_3Sn phase.

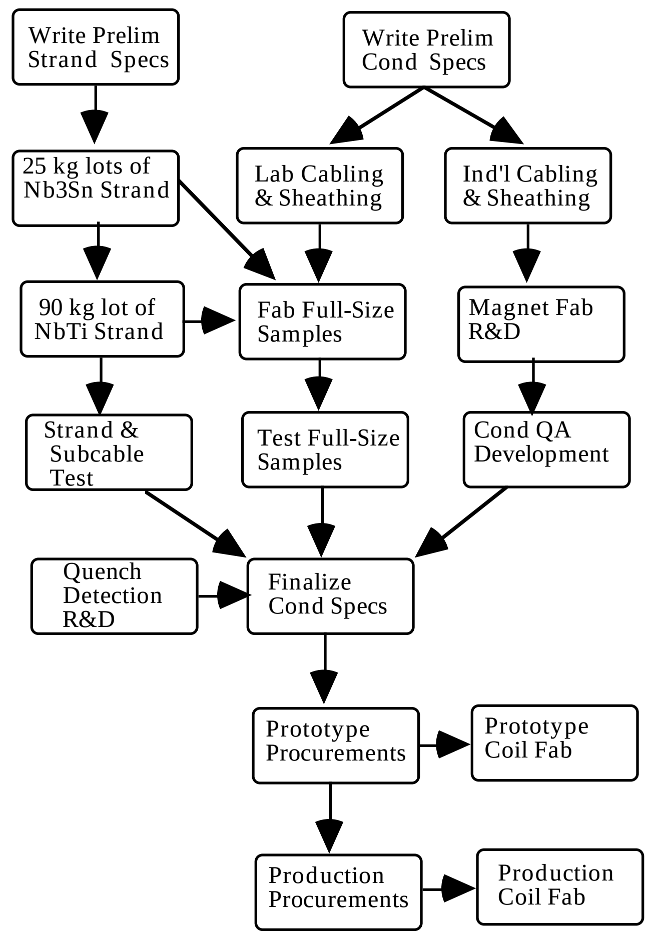

Fig. 4 The TPX Conductor Development Plan

STRAND DEVELOPMENT STATUS

The development of the superconducting strand proceeded as outlined in a paper presented at the previous SOFE conference [10], although the parameters were changed to reflect the changes in the magnet design. Also, we only purchased 90 kg of Nb-Ti vs the 250 kg lot previously proposed to keep our development costs within budget. Table 2 below presents the parameters of the preliminary strand specifications used to procure multiple 25 kg lots of Nb_3Sn strand and the single 90 kg lot of Nb-Ti strand.

Table 2
TPX Preliminary Strand Requirements

Parameter	Units	TF	CS/PF-5	PF-6/PF-7
Conductor Type		Nb_3Sn	Nb_3Sn	Nb-Ti
I_c @ 4.2 K, 10 μV/m	A	148	138	550
Field to Measure I_c	T	9	8	5
n value		> 20	> 20	> 20
Diameter	mm	0.78±0.01	0.78±0.01	0.78±0.01
Copper : noncopper ratio		2.5 ± .2	3.5 ± .2	2.5 ± .2
Cr plating thickness	μm	1 ± .5	1 ± .5	1 ± .5
Final RRR		> 75	> 75	> 150
Twist Pitch, Right Hand[(a)]	mm	9 ± 1	< 10	9 ± 1
Hysteresis loss, ± 3 T,	mJ/cc (noncopper vol.)	< 550	< 550	< 150
Piece Length	m	> 1500	>1100	>3300

Note: (a) In follow-on specifications this will be changed to 12±1 mm.

The strand development program was very successful, since two vendors were able to produce strand fully compliant with both Nb_3Sn specifications and our single Nb-Ti vendor met the Nb-Ti specifications. Both of the Nb_3Sn compliant materials were made using the internal tin approach. One bronze-route strand came within 80% of the critical current specification, and had some trouble in meeting the piece length requirement. The conjecture was that the critical current specification might be met by a billet redesign and a longer twist pitch could solve the piece length problem, but there was no time or funds to pursue this. On the Nb-Ti front, the vendor did have some initial piece length problems, but they were eventually overcome by finding a suitable thermomechanical sequencing. Lengthening the twist pitch to 12 mm from the specified 9 mm would probably lessen the probability of strand breakage during processing.

STRAND & SUBCABLE TESTS

A limited amount of strand testing to supplement the vendor-supplied data was carried out by MIT, and the measurements supported the vendor data. At least two interesting phenomena have been discovered in the course of carrying out the tests beyond the conventional tests to confirm the vendor data. The first is that the critical current increases upon successive cooldowns and retests, which suggests that the residual compressive strain decreases upon repeated cooldowns [11-12]. To the best of our knowledge, this has not been observed before and may be related to the large volume of copper stabilizer incorporated in the TPX Nb_3Sn strand. The second interesting observation is an apparent connection between heat treatment conditions and the peak compressive prestrain. Measurements of prestrain on two samples of 3.5:1 strand from one vendor exhibited significantly different levels of prestrain, i.e., 0.42% vs. 0.30% [13]. The only apparent difference in these 2 specimens was the heat treatment conditions; the sample with the higher prestrain was ramped to 660 C in a stepwise fashion (average rate of 60 C/hour) and then furnace cooled after 240 hours at 660 C, whereas the other sample was continuously ramped at 60 C/hour to 660 C and then cooled at 50 C/hour to 400 C. It appears that the latter heat treatment allows for some relaxation to take place, probably by creep of the copper stabilizer [14]. More work needs to be done in order to understand these effects.

A series of dc and pulse tests were performed on cables consisting of 27 strands (18 CS Nb_3Sn strands and 9 OFHC copper strands) simulating the CS conductor [15-16]. In contrast to earlier experiments using US-DPC material, no ramp rate limitations or quenches were observed for conditions simulating TPX charge/discharge requirements. The subcable critical current values were slightly lower than predicted from the single strand measurements, and there was some further degradation upon ramping, but these values were difficult to determine experimentally so further work would be needed to accurately quantify this. High-current quenches were obtained by setting the sample current and ramping the background field; the values of power balance for these quenches lends support to the suitability of the TPX power balance criterion of 1000 W/m^2-K.

FULL-SIZE CONDUCTOR TESTS

Work is in progress on fabrication and testing of full-size conductors to verify the conductor design assumptions as early as possible. Three 3.5-m-long TF-type conductors have been produced by LLNL personnel on the LBL cabling machine. One of these conductors is made from sub-specification Nb_3Sn strand and sheathed with 316LN. This is a practice piece that is used to checkout the various steps in the sample production process to eliminate problems in making the real test samples. The "real" samples have Incoloy 908 conduits; one sample features 486 strands of 2.5:1 TF strand, cabled in a 3x3x3x3x6 pattern the other is a hybrid cable of 486 strands, in which one strand in each starting triplet is OFHC copper and the other two are 1.8:1 TF strand. This allows us to assess two cable configurations in one test since the actual test article consists of one leg of each type, connected at the lower end by a 0.5-m-long joint.

The samples will be heat treated in a newly-acquired tube furnace at LLNL. A major concern is the elimination of cracking in the Incoloy 908 conduit due to grain boundary oxidation; we plan to overcome this problem by performing the heat treatment with the open-ended sample under vacuum in a retort; we have verified this process on small and large scale tests.

The conductor tests will be performed in a Pulse Test Facility (PTF) now under construction at MIT. The facility will provide a 8.4 T peak transverse field with a flat top of about 30 sec. We plan to provide copper coils which will provide a pulsed longitudinal field while the transverse field is applied. In this facility the TPX operational conditions can be simulated, giving us experimental verification of the TPX conductor design.

INDUSTRIAL CABLING AND SHEATHING

We are carrying out a considerable industrial effort in conductor manufacturing. Although we had assumed at the outset of the program that the sheath would be formed by welding strip around the cable in a continuous process, we allowed proposals to be submitted using other processes. The winning proposal in our competitive procurement process is based on a process in which the cable is inserted into sections of tubing, and the lengths of tubing are joined by orbital butt welding. The tubing is formed around the cable by die drawing with a large diameter bullblock and spooled onto a large diameter spool. The cable, included in this contract, is made from OFHC strand, some of which is Cr plated, and includes co-wound stainless steel wires as dummy quench detection sensors and was intended to mimic the TPX cable specification which was in work at the time this contract was placed.

Work is presently underway to produce TF-type demonstration conductor; 200 m of tubes were loaded with cable and the welding/drawing/spooling operations were underway. After the 200 m of TF-style demonstration conductor are completed, the machine will be used to produce 500 m of CS-style conductor. Based on the development tests that have been carried out, we are confident that this method will be capable of producing reliable CICC since the amount of welding required is much less than the conventional tube mill approach and the non-continuous production method allows for the development of sensitive QA inspection techniques with the possibility of repair before the conduit is formed around the cable.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of K. I, Thomassen, J. Sinnis, and J. Schmidt (TPX Project Office), S. Shen, J. Parker, R. Jenkins, and A. Horner at LLNL, R. Scanlan and H. Higley at LBL, and our Vendors, Everson Electric Co., Intermagnetics General Corp., Oxford Superconductors, Supercon, and Teledyne Wah Chang.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-48, and by Princeton Plasma Physics Laboratory under contract number DE-AC02-76-CH03073.

REFERENCES

[1] G. A. Deis, et al., "TPX Superconducting Tokamak Magnet System - 1995 Design and Status Overview," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[2] H. Calvin, et al., "TPX Superconducting PF Magnets," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[3] I. S. Hwang, R. G. Ballinger, M. M. Morra, and M. M. Steeves, in "Advances in Cryogenic Engineering (Materials)," Vol. 38, F. R. Fickett and R. P. Reed, eds., Plenum Press, New York, 1992, p. 1.

[4] R. P. Reed and A. F. Clark, eds., "Materials at Low Temperatures," ISBN: 0-87170-146-4, p. 378.

[5] I. Zatz and P. Bonanos, "TPX Structural and Cryogenic Design Criteria", TPX Doc # 94-950117-PPPL-IZatz-01.

[6] P. W. Wang, et al., "Numerical Modeling of the Voltage Sensors for Quench Detection in the TPX TF and PF Conductors," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[7] M. R. Chaplin, et al., "Co-Wound Voltage Sensor R&D for TPX Magnets," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[8] S. P. Smith and S. Pourrahimi, "A Fiberoptic Quench Detection System for Cable-In-Conduit Magnets," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[9] M. R. Chaplin, et al., "Local I&C for the TPX TF and PF Magnets," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[10] J. P. Zbasnik, et al., "The TPX Magnet R&D Program," proc. 15th IEEE/NPSS Symposium on Fusion Engineering, October 11-15, 1993, p. 794.

[11] M. Takayasu, "TPX IGC Wire Test Result Summary: Hysteresis Loss, RRR, and Critical Currents," TPX Doc. # 14-950914-MIT-MTakayasu-01.

[12] P. Michael, "Correlation Fit for IGC-TPX-PF Wire, Rev. 1," TPX Doc. # 14-950913-MIT-PMichael-03.

[13] J. Ekin, September 12, 1995 letter to M Takayasu.

[14] J. Ekin, private communication.

[15] S. Jeong, et al., "Ramp-rate Limitation Experiments and Analysis in Support of the TPX Magnets," 16th IEEE/NPSS Symposium on Fusion Engineering, September 30 - October 5, 1995, in press.

[16] J. H. Schultz and S. Jeong, "Interpretation of Ramp-Rate Limitation Experiments on IGC 3.5:1 Copper/Noncopper Hybrid Subcable," MIT Memo ITER/US/EV-MAG/J.Schultz/9.28/1.

Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551